



(19)

Europäisches Patentamt

European Patent Office

Office européen des brevets



(11)

EP 1 003 044 A2

(12)

## EUROPEAN PATENT APPLICATION

(43) Date of publication:  
24.05.2000 Bulletin 2000/21

(51) Int. Cl.<sup>7</sup>: G01R 15/16

(21) Application number: 99122147.4

(22) Date of filing: 05.11.1999

(84) Designated Contracting States:  
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU  
MC NL PT SE  
Designated Extension States:  
AL LT LV MK RO SI

(30) Priority: 10.11.1998 US 200353

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### (54) Method and apparatus for using shuttered windows in a micro-electro-mechanical system

(57) A windowed shutter (32) on a micro-electro-mechanical system improves output current of a non-contacting electrostatic voltmeter (v). The output current is increased by increasing the area modulated by the micro-electro-mechanical shutter system and by increasing the speed of that modulation. The increase in the area modulated by the windowed shutter is in direct

proportion to the number of windows (34) used. Moreover, the speed of the modulation is increased by increasing the resonant frequency of the system. Less shutter mass increases the frequency thus increasing shutter movement over time.

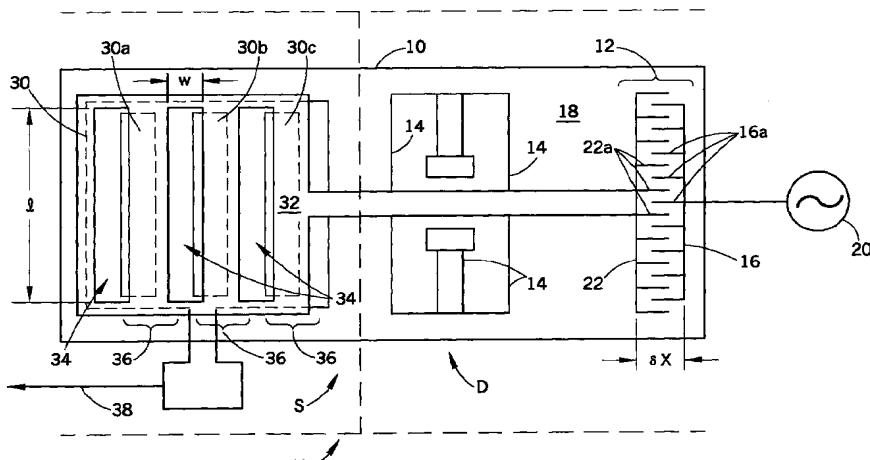


FIG.1

**Description**

[0001] In an effort to achieve reliable, low cost, and potentially high precision micro sensors, development continues in the technology of integrating small mechanical elements onto silicon substrates. Polysilicon microbridges have been driven vertically and laterally as resonant microsensors. With respect to laterally driven microbridges, short displacements of a comb type drive of the type shown and described in U.S. Patent No. 5,025,346, typically on the order of one to ten micrometers, lead to very weak sensed signals. The disclosure of the 5,025,346 patent is incorporated herein by reference.

[0002] One such class of devices hampered by the weak output signals is electrostatic voltmeters (ESV's). Non-contacting ESV's are utilized, for example, within xerographic printers to measure the surface voltage of the photoreceptor; however, additional applications are known in the art. In almost all non-contacting voltmeters the measurement of the surface voltage is made using capacitive coupling of a sense probe to the measured surface. This capacitive coupling is typically modulated by a mechanical shutter between the sense probe and the measured surface. The output current of a capacitively coupled sense probe is given by:

$$i_s(t) = dQ(t)/dt = d/dt[C(t)V_s(t)] = C(t)dV_s(t)/dt + V_s(t)dC(t)/dt, \quad \text{EQ.1}$$

where  $Q(t)$  is the time-varying charge induced on the sense probe,  $C(t)$  is the time-varying capacitance and  $V_s(t)$  is the time-varying measured surface voltage. For the measurement of the d.c. component of the photoreceptor voltage,  $V_{dc}$ , the equation can be simplified to:

$$i_s(t) = V_{dc}dC(t)/dt = V_{dc}[\partial C(x,t)/\partial x][\partial x/\partial t], \quad \text{EQ. 2}$$

where the shutter position determines  $C(t)$  at any time. For a sinusoidal drive signal the capacitance is given by:

$$C(t) = C_o + C_m \sin(\omega t). \quad \text{EQ. 3}$$

Here  $C_o$  is the d.c. component of the capacitance that does not change with time and  $C_m$  is the a.c. component of the capacitance that changes with the shutter motion. To maximize the signal, either the change in the capacitance with respect to shutter position (i.e.  $\partial C(x,t)/\partial x$ , from EQ. 2) or the shutter velocity (i.e.  $\partial x/\partial t$ , from EQ. 2), or both, can be increased.

[0003] Since, the shutter is typically operated at resonance, the resonant frequency determines the shutter velocity,  $\partial x/\partial t$ . On the other hand, shutter geometry determines the change in capacitance with respect to shutter position. Previous micro-electro-mechanical ESV's employ a simple shutter that masks a portion of the sense probe. The shutter is actuated by an electrostatic comb type drive, which typically has a maximum displacement,  $\delta x$ , on the order of 1-10  $\mu\text{m}$ .

[0004] In such a design the modulated change in the capacitance is determined by the permittivity of freespace  $\epsilon_0$ , and the area  $A$ :

$$C(t) = C_o + (\epsilon_0 \delta A/d) \sin(\omega t) = C_o + (\epsilon_0 \ell \delta x/d) \sin(\omega t), \quad \text{EQ. 4}$$

where  $\delta x$  is the displacement of the shutter, and  $\ell$  is the length of the shutter, for a spacing  $d$  between the sense probe and the photoreceptor.  $\delta x$  is limited by the displacement of the comb drive. Thus, to increase the modulated area the length of the shutter,  $\ell$ , can be increased. However, increasing the length of the shutter,  $\ell$ , will correspondingly increase the size and mass of the resonator, leading to a decrease in sensor spatial resolution and a lower mechanical resonant frequency. This has the undesirable effect of reducing sense probe current output.

[0005] Thus, an alternative solution has been sought that provides a larger effective modulation area in order to obtain a stronger signal than previous designs.

[0006] The present invention contemplates a new and improved apparatus which overcomes all of the above-referenced problems and others, providing a higher output current.

[0007] In accordance with the present invention there is provided an electrostatic voltmeter which includes a sense probe assembly having a plurality of sense probes for measuring voltage by capacitive coupling. A shutter having a plurality of windows is also included and is moveable between a first position where the sense probe assembly is exposed and a second position where the sense probe assembly is covered. The shutter is located adjacent to the sense probe assembly. Additionally, a shutter modulator is operatively associated with the shutter and is capable of selectively moving the shutter between the first position and the second position.

[0008] According to another aspect of the present invention, the shutter modulator includes a micro-electro-mechanical system which contains an electrostatic comb drive. The comb drive defines a maximum displacement along an axis parallel to the comb fingers. The windows in the shutter further define a width equivalent to that of the maximum

displacement of the comb drive.

[0009] In accordance with still another aspect of the present invention, a method of increasing an output signal produced by a non-contacting voltmeter is provided. A moveable shutter is placed adjacent to a plurality of sensed probes. The moveable shutter has a plurality of windows spaced therein to expose the sense probes in a first position and to cover the sense probes in a second position. The shutter is then moved between the first and second positions thereby increasing the output signal produced.

Figure 1 is a depiction of an electrostatic voltmeter according to the present invention;  
 Figure 2 is a schematic view of an electrostatic copier/printer incorporating the electrostatic voltmeter; and  
 10 Figure 3 is a detail of the voltmeter from Figure 2.

[0010] The FIGURES show a voltmeter **V** that generally includes a driver component **D** and a sensor component **S**. More specifically, and with particular reference to FIGURE 1, a microstructure 10 has a driver component **D** configured as a comb drive 12 with a cantilevered spring arrangement 14. The comb drive 12 is a common mechanism for electrostatically driving microstructures and includes a fixed side 16 attached to a substrate 18. The comb drive is electrically connected to an electrostatic drive signal source 20. A movable side 22 of the comb drive is held to, but above, the substrate 18 by the cantilevered spring arrangement 14. A plurality of comb "fingers" 16a, 22a are interdigitated to provide electrical communication between the fixed side 16 and the movable side 22. The length of these fingers define a maximum potential displacement,  $\delta x$ .

20 [0011] The driver component **D** shown in FIGURE 1 is understood to be merely a representative structure that would fulfill the objects of the present invention. However, other driver components are also encompassed by this disclosure such as magnetostatically and thermally driven microstructures among others.

[0012] Operatively associated or connected to the driver component **D** is the sensor component **S**. In this preferred embodiment, the driver component **D** is disposed opposite or linearly adjacent the sensor component, although it will be appreciated that other geometric arrangements may be used without departing from the scope and intent of the subject invention. A sense probe assembly 30 is fixed to the substrate 18 and is capable of capacitive coupling with a surface to be measured. The sense probe assembly is a set of spaced individual sense probes (represented here by numerals 30a, 30b, 30c, etc.) The individual sense probes are connected together so that individual signals are combined. The sensor component **S** further comprises a movable shutter 32 that selectively overlays the sense probe assembly 30. Here, the shutter is mechanically connected to driver component **D** so that linear displacement of the driver component results in a corresponding displacement of the shutter. The shutter 32 has a plurality or set of openings or windows 34 configured such that the sense probe assembly 30 is selectively exposed through the windows 34 when the shutter 32 is in a first position. The individual shutter openings are spaced from one another by a dimension matching the individual sense probe spacing. When the shutter 32 is in a second position, the sense probe assembly 30, or individual sense probes, is/are covered by the shutter regions 36 interposed between the windows. In other words, when the shutter 32 is in the first position, capacitive coupling by the sense probe assembly 30 is permitted. On the other hand, when the shutter is in the second position capacitive coupling by the sense probe assembly is masked or inhibited. The current generated by the sense probe assembly 30 is output on line 38.

[0013] The windows 34 define a length  $l$  and a width  $w$ . In a presently preferred embodiment, the width  $w$  is on the order of 10 $\mu$ m and is slightly less than the maximum potential displacement  $\delta x$ . Similarly, each shutter region 36 separating the windows is substantially equal to the maximum potential displacement  $\delta x$ .

[0014] One skilled in the art can now appreciate that this change in geometry has the desirable effect of using a small drive displacement,  $\delta x$ , to advantageously provide a greater change in the modulated area. Said another way, the modulated area is  $(n)(\delta x)(l)$ , or  $n$  times as large as the shutter without windows (where  $n$  is the number of windows 34 in the shutter 32). For ease of reference, a modification of Equation 4 is shown here so that the benefit of increased area may be appreciated mathematically:

$$C(t) = C_0 + \varepsilon_0 \delta A / d \sin(\omega t) = C_0 + \varepsilon_0 n l \delta x / d \sin(\omega t), \quad \text{EQ. 4'}$$

50 This increased area desirably increases the output signal.

[0015] The windows in the shutter 32 also contribute to increase the output signal. The windows make the shutter lighter, i.e., decreased weight, thus increasing the resonant frequency of the sense probe system. It follows that increased frequency ( $\omega$ ) yields increased shutter velocity ( $\delta x/\delta t$ ) as shown by the following equations:

$$x = x_0 \sin(\omega t), \quad \text{EQ. 5}$$

thus,

$$\frac{\partial x}{\partial t} = \omega x_0 \cos(\omega t),$$

EQ. 6

and

$$i_s(t) = V_{dc} dC(t)/dt = V_{dc} [\partial C(x, t)/\partial x] [\partial x/\partial t], \quad \text{EQ. 2}$$

Therefore, increased velocity in turn yields an increased output signal.

[0016] Referring now to FIGURE 2, a xerographic type copier/printer 40 includes a photoreceptor 42 configured as a rotating drum. The present invention recognizes that other photoreceptor configurations, such as belts or webs are possible. A charge station 44 is provided where photoreceptor 42 is charged in preparation for imaging. During any of various operations (copying, printing, etc.), the photoreceptor 42 travels a path adjacent the voltmeter V after which an electrostatic image is placed on the photoreceptor 42. Next, the photoreceptor 42 proceeds to a developer station 46 where the latent image created on the photoreceptor 42 is developed followed by a transfer station 48 where the previously developed image is transferred to a copy sheet 50. Residual developer materials are removed from the photoreceptor 42 at cleaning station 52 prior to charging again at the charge station 44. Details of the xerographic device and method of operation are generally known to those of ordinary skill in the art and the particular details form no part of the present invention.

[0017] FIGURE 3 shows a cross-section of the voltmeter V in the copier/printer 40 as described above. Cross-referencing FIGURE 1, the voltmeter V contains a comb drive 12 with a fixed side 16 attached to a substrate 18 and a movable side 22 movably attached to the substrate via a cantilevered spring arrangement 14. The sense probe assembly 30 is shown attached to the substrate 18 with the movable shutter 32 between the substrate and the photoreceptor 42.

[0018] Figures 2 and 3 are merely one representative example of the use of the present invention in a practical environment. The general principles, though, may be applied to related environments or applications. For example, flat panel display applications can incorporate the principle of the modulating light between first and second surfaces. Likewise, the preferred embodiment employed a single MEMS modulator in the electrostatic voltmeter application. However, one skilled in the art will readily appreciate the application of these principles to an array of modulators. For example, in an effort to sense and control page width, an array of modulators can be used to sense photoreceptor voltage at discrete locations. Moreover, although the displacement described with reference to the preferred embodiment of FIGURES 1-3 is linear, embodiments using angular displacements are also contemplated and deemed to fall within the scope hereof.

## Claims

### 1. An electrostatic voltmeter comprising:

a sense probe assembly for measuring a voltage by capacitive coupling;  
 a shutter defining a plurality of windows movable between a first position where the sense probe assembly is exposed and a second position where the sense probe assembly is covered, the shutter being adjacent to the sense probe assembly; and  
 a shutter driver operatively associated with the shutter for selectively moving the shutter between the first position and the second position.

### 2. The electrostatic voltmeter of claim 1 where each of the plurality of windows defines a length (l) perpendicular to the comb fingers and a width (w) parallel to the comb fingers, the width being equal to the maximum displacement.

### 3. A method to increase an output signal produced by a non-contacting voltmeter comprising:

providing a plurality of sense probes;  
 placing a movable shutter adjacent to the sense probes, the shutter defining a plurality of windows spaced to expose the sense probes in a first position, and cover the sense probes in a second position; and  
 moving the shutter between the first position and the second position.

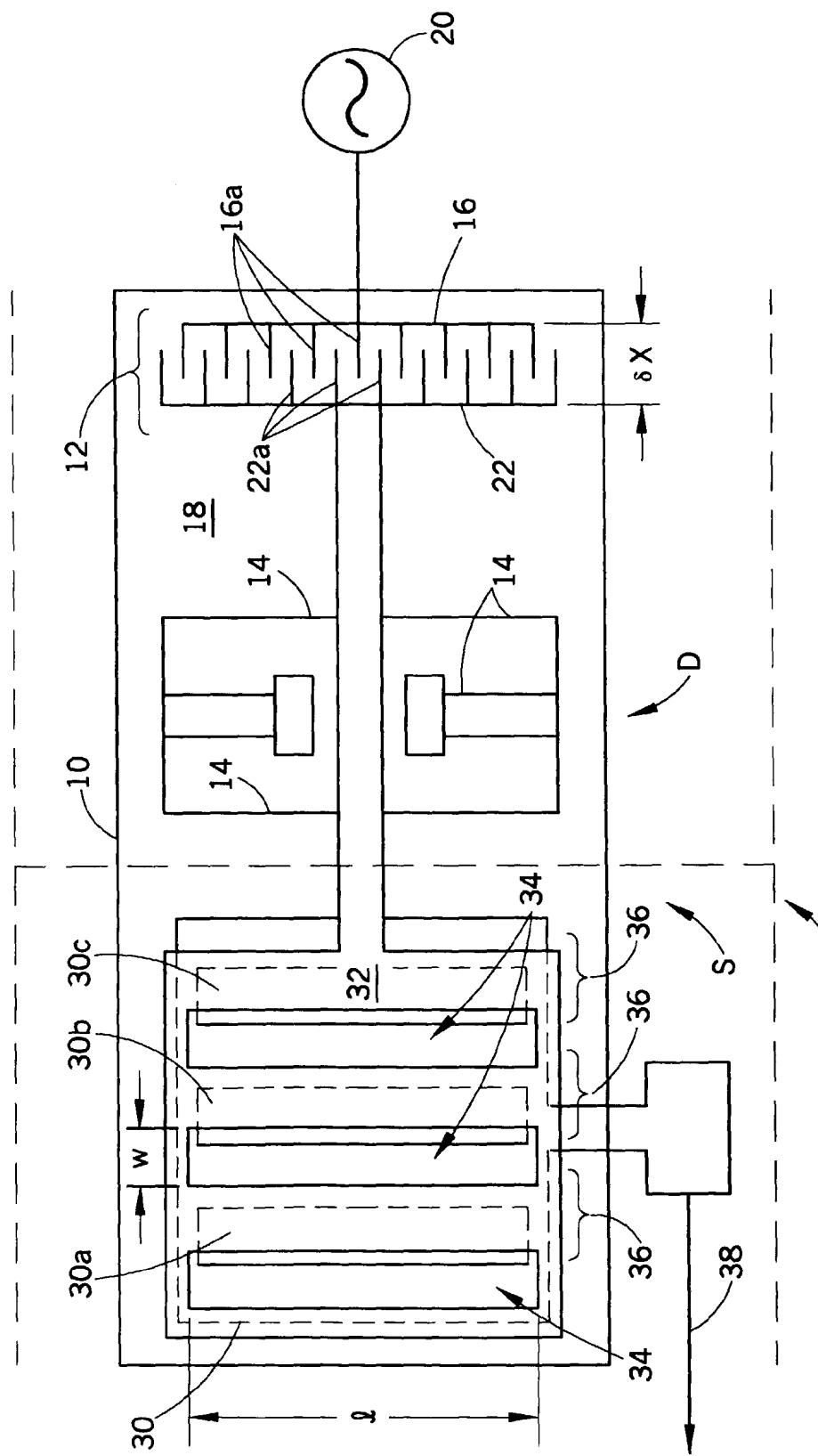


FIG. 1

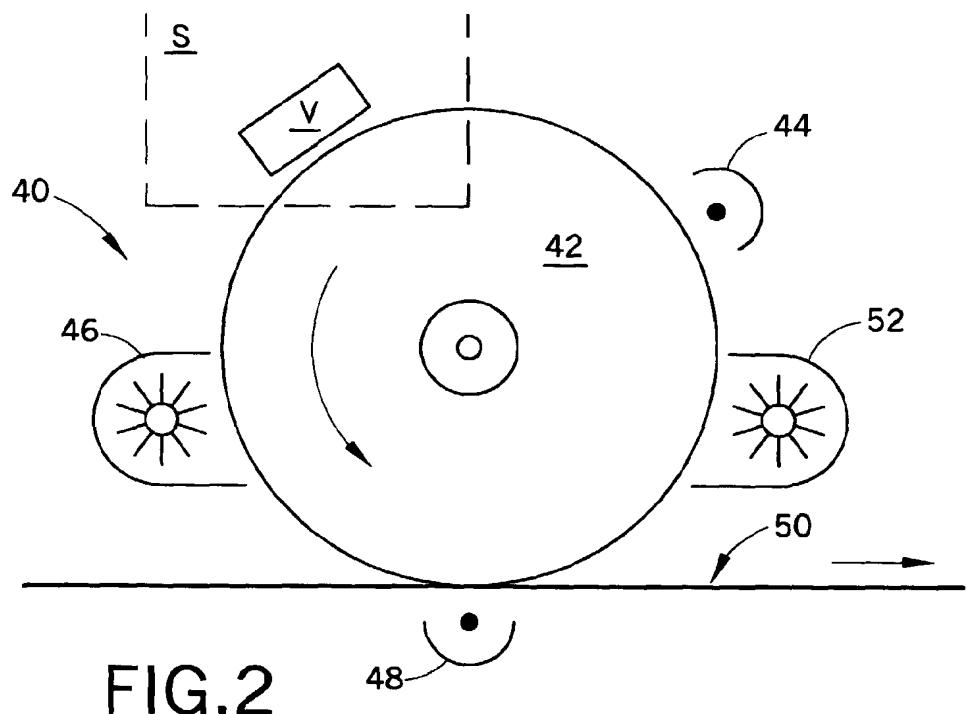


FIG.2

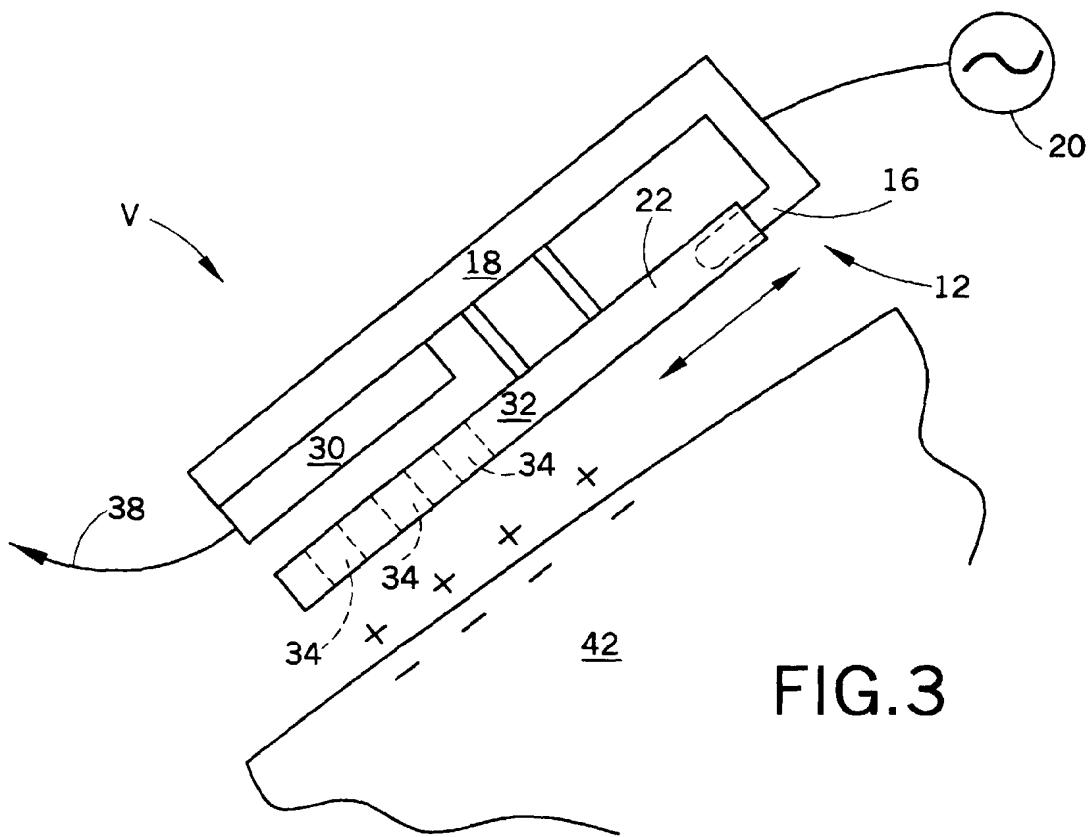


FIG.3